Design of a Propulsion System Test Facility to Study Rocket Plumes in the Space Environment

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ABSTRACT

NASA has initiated a project at JPL for the design and fabrication of a facility to test various types of propulsion systems in the vacuum environment of space. The Propulsion Contamination Effects Module (PCEM) Spaceflight Experiment is being designed for installation in the payload bay of the Space Shuttle Orbiter. The objectives of the experiments are to measure exhaust plume characteristics and surface impingement effects from high-thrust chemical and low-thrust electric thrusters. The PCEM facility will include sensors for measuring several parameters. Included as instruments are temperature-controlled quartz crystal microbalances and a mass spectrometer. The experimental data will be used to demonstrate the ability of analytical models to predict forces, heat fluxes, surface charging effects, and levels of contamination which might be encountered by a spacecraft employing these thrusters. Measurement emphasis will be placed upon the backflow region of the plume. This area is of primary concern to the spacecraft designer, and yet it represents an area of maximum theoretical ambiguity.

The initial PCEM configuration will be designed to accommodate a 110 N (25 lb_f) monopropellant hydrazine propulsion system. Design modification kits will enable the PCEM to accommodate other propulsion systems, including a 3870 N (870 lb_f) N_2O_4/MMH liquid bipropellant rocket engine, 4.4×10^{-3} N (1×10^{-3} lb_f) and 1.3×10^{-1} N (3×10^{-2} lb_f) ion drive engines, a 4450 N (1000 lb_f) solid rocket motor, and a 110 N (25 lb_f) O_2/H_2 gaseous bipropellant system.

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology under Contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.

1.0 INTRODUCTION

The need for the development of a capability for providing basic experimental data to verify plume models utilized in the design of spacecraft is evident. The necessity exists because of the limitations inherent in existing experimental facilities and analytical models.

The problems resulting from the effects of rocket engine plumes and plume contaminants on spacecraft systems and instruments have long been recognized by NASA, and studies have been initiated to define and resolve the problem. A NASA (GSFC) Nimbus study was authorized in 1970, and one conclusion from the report (Ref. 1) was: ". . . space simulation chambers will not achieve vacuums even remotely resembling those which occur in space. Yet, it is precisely this very high vacuum which enables the phenomenon to occur which we are undertaking to study. . . . This consideration leads us to the most accurate investigation, namely, a flight experiment. Here, we need not worry about environment since it is there. . . . Our overall conclusion is that further work is needed. . . . We feel that some work in the analytical direction and some work in the experimental direction both are needed." The propulsion technology group of the OAST Space Technology Workshop (Summer Workshop) held at Harrisonburg, Va., in August 1975 recognized thruster-induced backflow contamination as a Justification Category I problem. This category specifies "space environment essential" for resolution. The JANNAF and the Workshop Steering Committees have sponsored plume technology conferences in which the results of many investigations were evaluated. Consequently, there has been an evolution in the advancement of plume technology. However, modeling data for spacecraft design is considered to be limited and the extrapolation of empirical data from mini-thrusters [≤0.9 N (0.2 lb_f)] tested in vacuum chambers to larger thrust engines [>200 N (50 lb_f)] in space is considered highly questionable, at best.

Numerous plume-associated anomalies have been observed on such NASA spacecraft as Nimbus, ISCE, ATS, Landsat-C, and Voyager. Voyager experienced the most recent problem as was reported in Ref. 2. Significant cost and performance impacts resulted from these problems. NASA and the Air Force are supporting investigations in the field of propulsion plume technology, and the Workshop Steering Committee priority area entitled "Payload Environments" includes work related to plume technology.

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1. Lyon, W. C., "Thruster Exhaust Effects Upon Spacecraft," NASA-TM-X-65427, Goddard Spaceflight Center (Oct. 1970), p 23.

2. "Voyager Controllers Grappling with Maneuverability Problem," Aviation Week and Space Technology, 107 (No. 14):41 (Oct. 3, 1977).

JPL has conducted studies and experiments for both NASA and the Air Force in the plume technology field. In the studies of Refs. 3, 4, 5, and 6 the JPL Molsink facility was utilized. This is an ultrahigh vacuum facility with an operating pressure range of 1.3×10^{-7} to 1.3×10^{-3} Pa (10^{-9} to 10^{-5} torr), although 1.3×10^{-4} Pa (10^{-6} torr) is a more typical background pressure when testing a 0.9 N (0.2 lb_f) monopropellant hydrazine thruster in the pulse mode (Ref. 6).

In an Air Force report (Ref. 7) on an attitude control rocket [98 N(22 lb_f)] exhaust plume experiment, Boudreaux and Etheridge investigated the effects of exhaust gases on spacecraft surfaces and spaceborne equipment. They reported that the Air Force facility utilized for the tests was capable of simulating an altitude of 53 km (174,000 ft) and with the engine firing, a steady-state altitude of 46.3 km (152,000 ft) was demonstrated. The authors noted the limitations of the facility and in their conclusions recommended: "An in-flight experiment be undertaken to complete the technology development initiated in the first two phases of the program. Primary data gains are expected from the use of a space exhaust plume since impingement would include both normal and oblique flow without mantle compaction, and is not able to be simulated in the laboratory. . . ."

Other studies (e.g., Ref. 8) express concern for plume effects and have indicated a need for space testing. The Propulsion Contamination Effects Module (PCEM) Spaceflight Experiments will fulfill the

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3. Chirivella, J. E., and Moynihan, P. I., "Hydrazine Rocket Engine Plume Deposits Measured with Quartz Crystal Microbalances," Seventh JANNAF Plume Technology Conference, Huntsville, Ala. (April 1973), pp 691-706.

4. Chirivella, J. E., "Molecular Flux Measurements in the Back Flow Region of a Nozzle Plume," TM33-620, Jet Propulsion Laboratory, Pasadena, California (July 1973).

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6. Baerwald, R. K., and Passamanek, R. S., "Monopropellant Thruster Exhaust Plume Contamination Measurements," Publication 77-61, Jet Propulsion Laboratory, Pasadena, California (Sept. 1977).

7. Boudreaux, R. A., and Etheridge, F. A., "Attitude Control Rocket Exhaust Plume Experiment Final Report - Phases 1 and 2," AFRPL-TR-67-3, Air Force Rocket Propulsion Laboratory (Feb. 1967).

8. Boynton, F. P., "Exhaust Plumes from Nozzles with Wall Boundary Layers," J. Spacecraft, 5 (No. 10): 1143-1147 (Oct. 1968).

requirements for space experiments as suggested in the above references and by various NASA Centers. PCEM is designated as a NASA payload category AE/SA-B (attached experiment/space available, class B) experiment facility. The primary design objective is to fly the PCEM system (i.e., facility with propulsion system) in the Shuttle bay, conduct the experiment, and safely return it to earth. Orbits, dependent upon inclination and cargo weight, will tentatively be on the order of 280-460 km (150-250 NM). The facility will have the capability of testing rocket propulsion systems at steady state thrust levels of up to 4450 N (1000 lbf). Operations related to the propulsion system test will be essentially automatic and, in the event the automatic sequencing malfunctions, the system will shut down safely and will be returned for problem evaluation, repair, and reflight on another mission. The PCEM should thus provide an excellent addition and extension to the capabilities of existing ground test facilities.

2.0 DISCUSSION

2.1 Objectives

The prime objective of the PCEM Project is to determine the effects of plumes from various types of thrusters under actual space conditions and to utilize the data thus obtained to build a predictative capability covering these effects. The PCEM instrument measurement systems will be used to measure core flow and backflow efflux (mass and constituents), electrical charge buildup, and impingement forces and heating rates. The recorded experimental data will be added to the existing data base to determine the ability of analytical models to predict these same effects. These models will then be updated.

A secondary serendipitous objective is to characterize the propulsion system in the space environment. The PCEM will accommodate propulsion systems instrumented for performance characterization data.

2.2 Systems

The major hardware systems to be integrated for the PCEM experiments are the PCEM facility with associated ground support equipment (GSE), the rocket propulsion system and its GSE, and the Space Shuttle/Spacelab pallet and associated systems. The rocket propulsion systems include subsystems such as the thruster, the propellant feed system, the instrumentation system (i.e., pressure, flow, and temperature instruments for performance characterization), and the related support equipment. The rocket propulsion systems which are to be accommodated by the

PCEM for the experiments, along with the responsible NASA Centers, are as follows:

1. N_2H_4, 110 N (25 lb_f) monopropellant system, Marshall Space Flight Center (MSFC).
2. N_2O_4/MMH, 3870 N (870 lb_f) liquid bipropellant system, Jet Propulsion Laboratory (JPL).
3. 4.5×10^{-3} N (1×10^{-3} lb_f/8 cm) Ion drive engine system, Lewis Research Center (LeRC).
4. Solid rocket motor (SRM), 4448 N (1000 lb_f), JPL.
5. O_2/H_2, 110 N (25 lb_f) gaseous bipropellant system, LeRC.
6. 1.3×10^{-1} N (3×10^{-2} lb_f/30 cm) Ion drive engine system, LeRC.

The monopropellant system is currently completing the development phase at MSFC. This propulsion system will be provided by MSFC and will include the propellant tank, feed system, and instrumentation system. The N_2O_4/MMH propulsion system was developed for the Space Shuttle Orbiter, Reaction Control Subsystem (RCS). This system will be incorporated into a modified package by JPL for the PCEM experiment and will include instrumentation for engine performance characterization. The 4.5×10^{-3} N (1×10^{-3} lb_f/8 cm) and 1.3×10^{-1} N (3×10^{-2} lb_f/30 cm) Ion drive engines are currently under development at LeRC. Each of these systems will be provided by LeRC as a package which will include the thruster, the propellant system, the power system, and instrumentation required for engine performance characterization. The solid rocket motor package will be prepared for PCEM installation by JPL and will include instrumentation for recording performance parameters. The O_2/H_2, 110 N (25 lb_f) gaseous bipropellant system is being developed by LeRC. This propulsion system will be provided by LeRC as a package which will include the thruster, propellant feed systems, tankage, and instrumentation required for engine performance characterization.

The PCEM facility consists of the structure assembly, the basic science instrumentation system, the control system, the electrical system, and the mechanical systems. The structure assembly provides mounting provisions for the propulsion system package, including the adapter and thrust alignment subsystem and possibly an elevating mechanism. One concept is depicted in Fig. 1. Figures 2 and 3 show two preliminary types of structural concepts. The structure also houses the control subsystem, the mechanical and electrical subsystems, and the basic science instrument subsystems, including associated refrigeration and controls. The initial PCEM facility will be designed to accommodate the MSFC monopropellant propulsion system. Subsequently, the facility will be refurbished with kits specifically designed to accommodate the other propulsion systems.

The basic instrument measurement systems considered for plume measurement during the space experiments are the temperature controlled quartz crystal microbalances, the mass spectrometer, the plume profile temperature and pressure probes, and surface collectors. The quartz

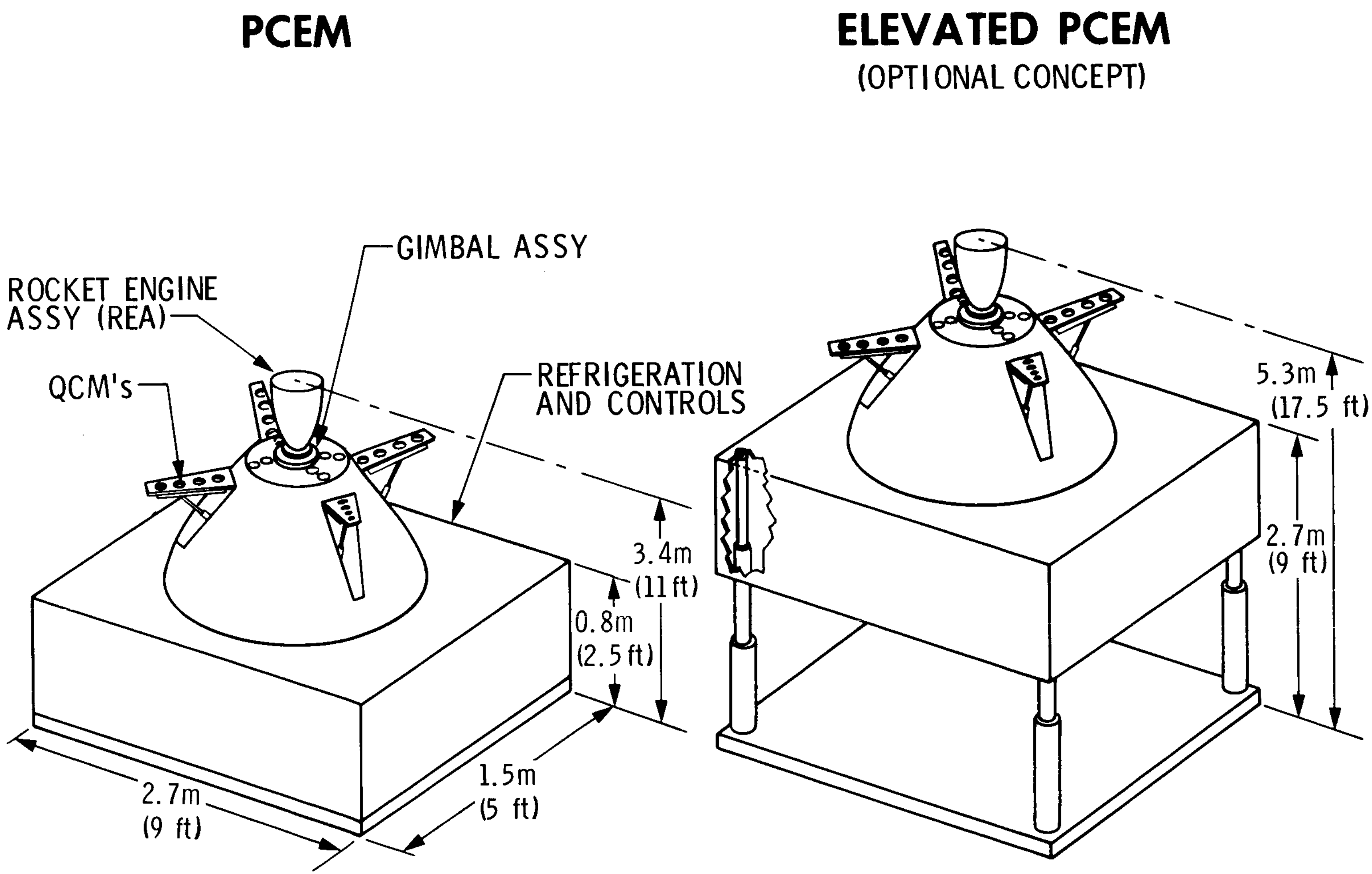


Figure 1. A PCEM Concept

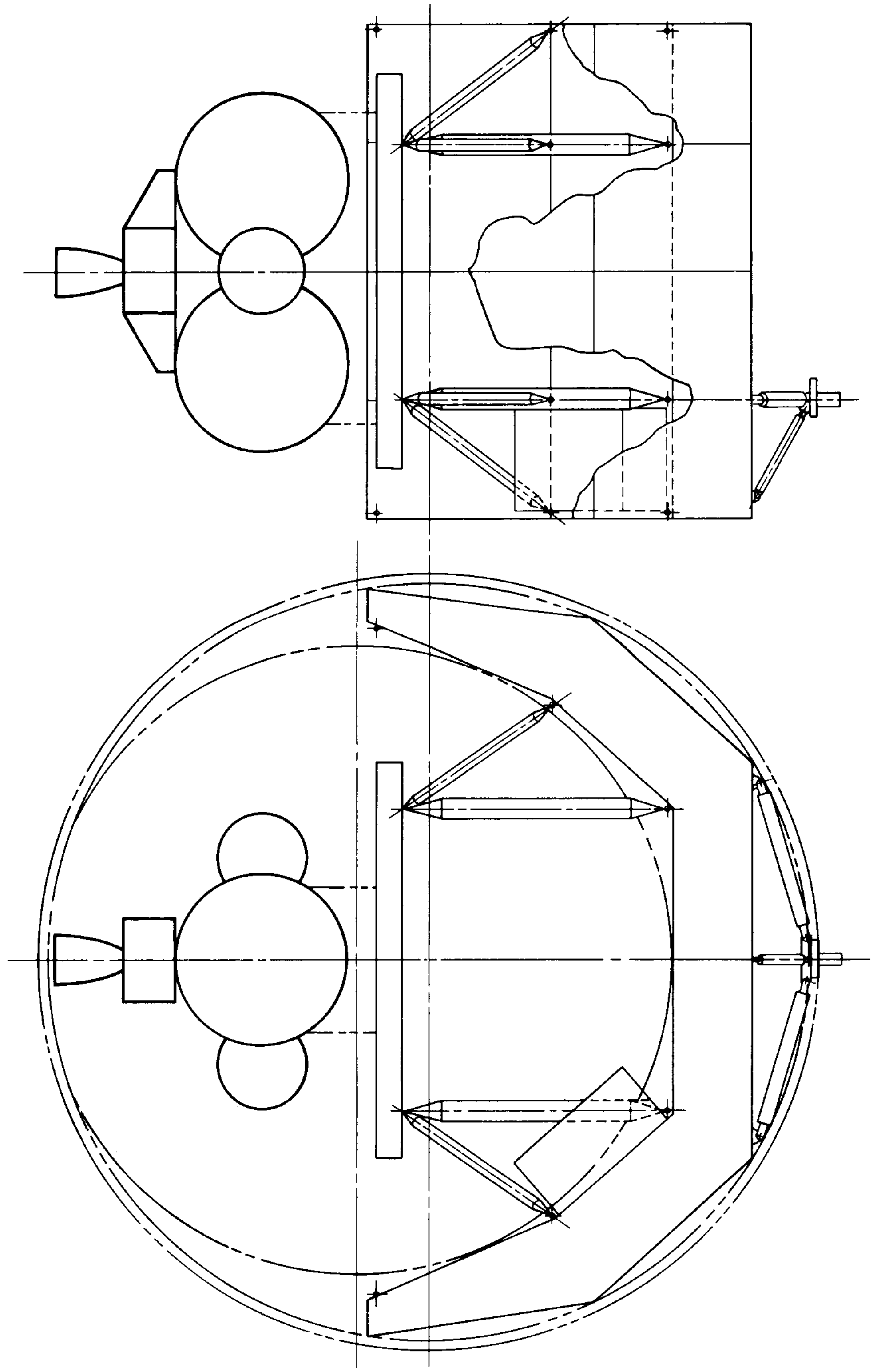


Figure 2. Fixed Structure

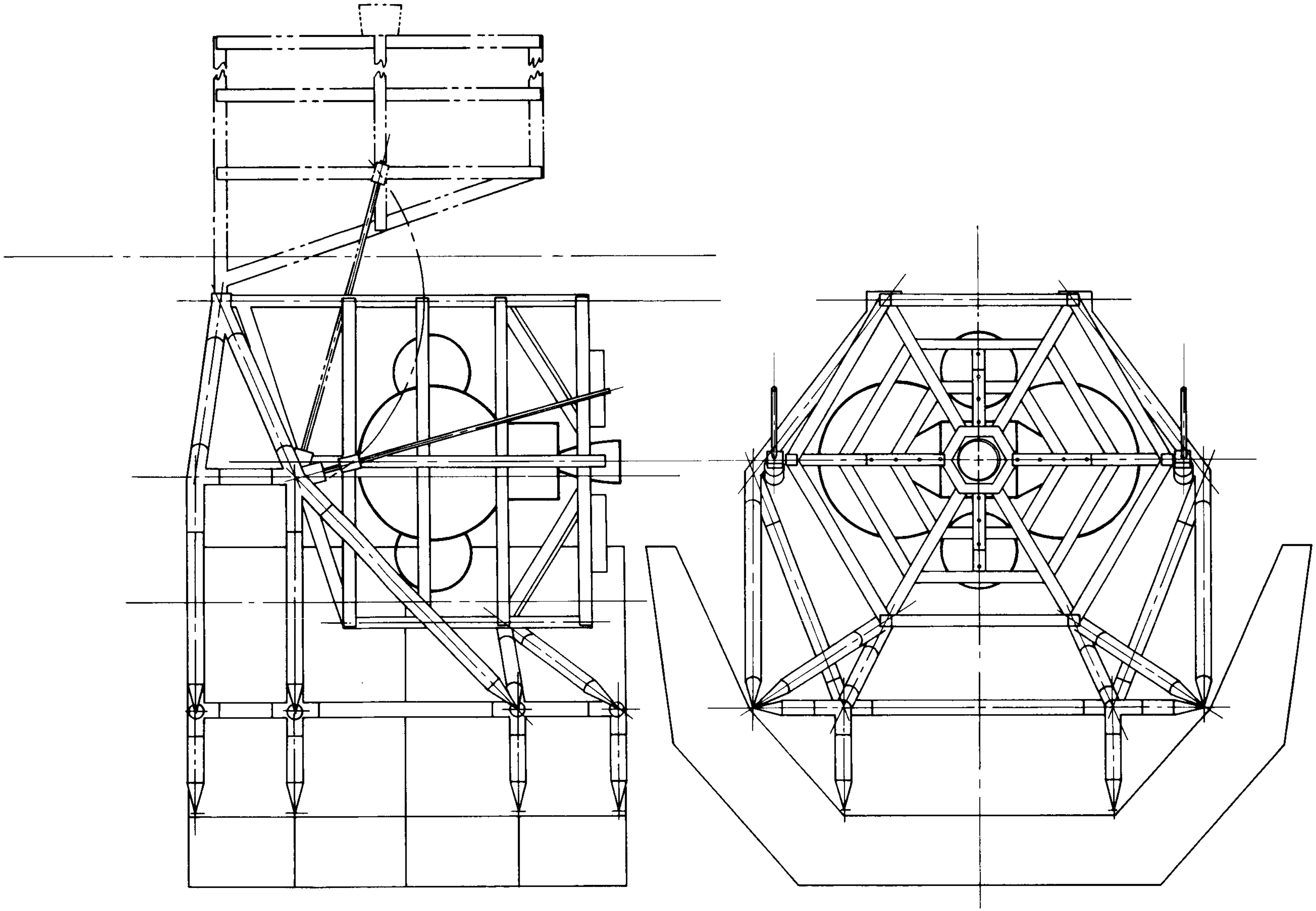


Figure 3. Deployable Structure

crystal microbalances will be used to measure the deposition rates of incident molecules at different crystal surface temperatures. The mass spectrometer system is to be used to measure flux of various gas species. The temperature and pressure probes will measure temperature and pressure levels at various locations in the plume profile. The surface collectors are passive units (i.e., tiles) which will be used for collection of contaminants deposited during the experiment and later analyzed in the laboratory. Other instruments may be supplied by the Principal Investigator (PI) for each of the experiments and could include, for example, a Langmuir probe and Faraday cups.

2.3 Technology

Testing in the space environment aboard Shuttle (see Fig. 4) and acquiring plume definition and performance characterization data, as proposed for PCEM, has not been previously conducted. However, the PCEM facility, the basic science instrumentation systems, and the propulsion systems all incorporate elements that are currently available and, therefore, no new advancements in the "state-of-the-art" are required. Much of the hardware and instrumentation required for the PCEM facility has been developed and included in one form or another on current or previous flight projects. Some items may, however, require additional design, modification, and verification testing to complete the PCEM system development for Shuttle/Spacelab integration. The requirements for the PCEM facility, the basic science instruments, and the prepackaged propulsion systems are described in the following paragraphs.

2.3.1 PCEM Facility Requirements. The PCEM facility will be designed for mounting to, and will utilize 80-100% of, a Shuttle/Spacelab pallet. Among the design tradeoffs to be considered (see Fig. 5) is the necessity for an elevating propulsion system mount to raise the thruster exit plane beyond the mold line of the Orbiter bay doors. Some primary considerations in this tradeoff are the electro-mechanical complexities, plume interaction effects with Shuttle mechanical systems and surfaces, the Shuttle contamination environment, solar wind effects, and Shuttle center of mass location with respect to the experiment thrust axis. Additional design areas which have yet to be worked include the data acquisition interfaces with Shuttle/Spacelab for test data recording by the Shuttle/Spacelab system, and the sequencing and control of the tests. Others are Shuttle/Spacelab TV-Film data recording, the interface with Shuttle/Spacelab power supplies, and other Shuttle/Spacelab interfaces, i.e., cold plates, dump system, and others as needed. The weighting factors attached to these design considerations will be dependent upon the definitions and requirements established by the PIs for the experiment science and the PCEM Design Team for structural and mechanical considerations. The GSE will be acquired primarily from existing sources.

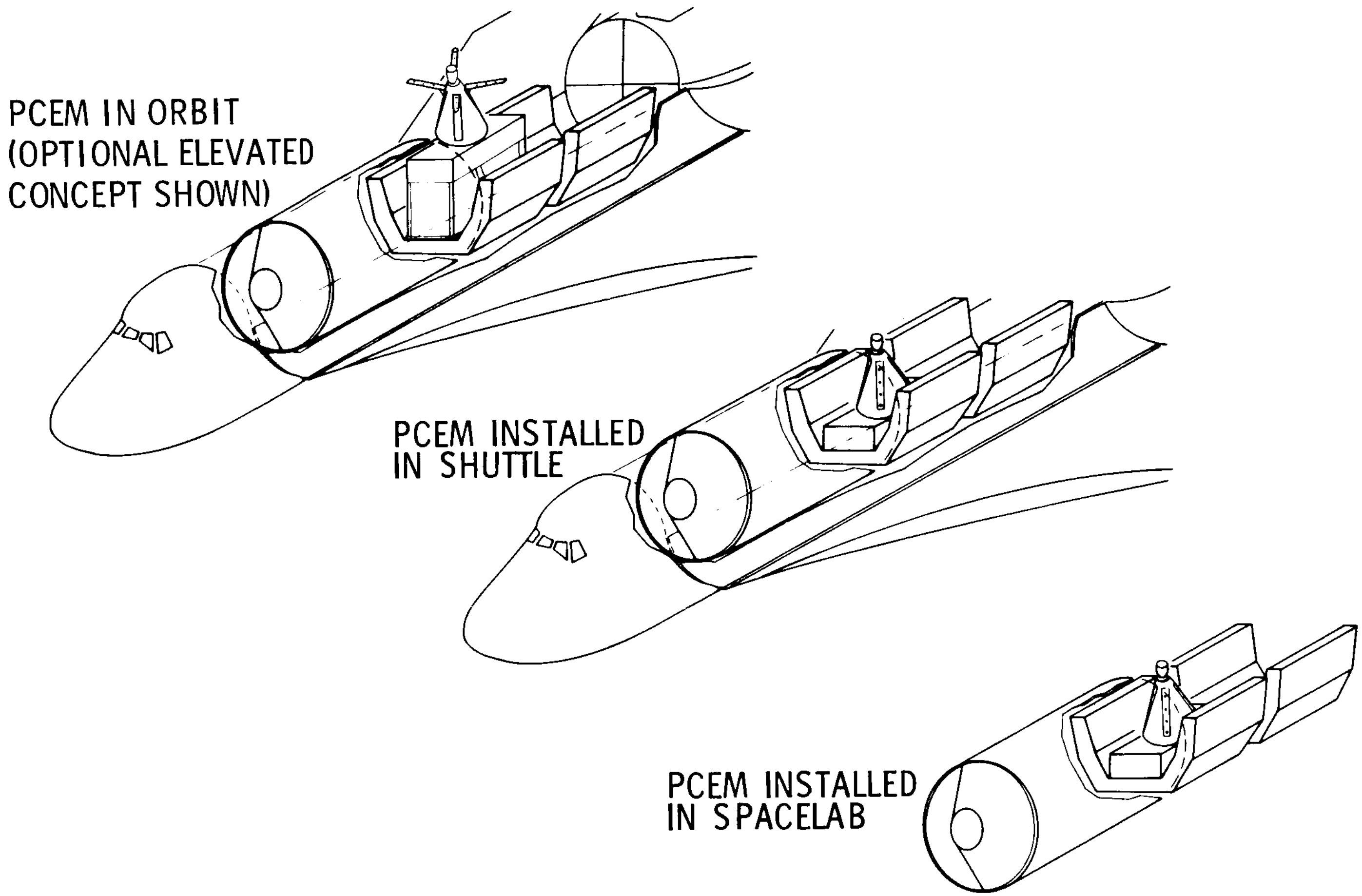


Figure 4. PCEM Experiment in Space Shuttle

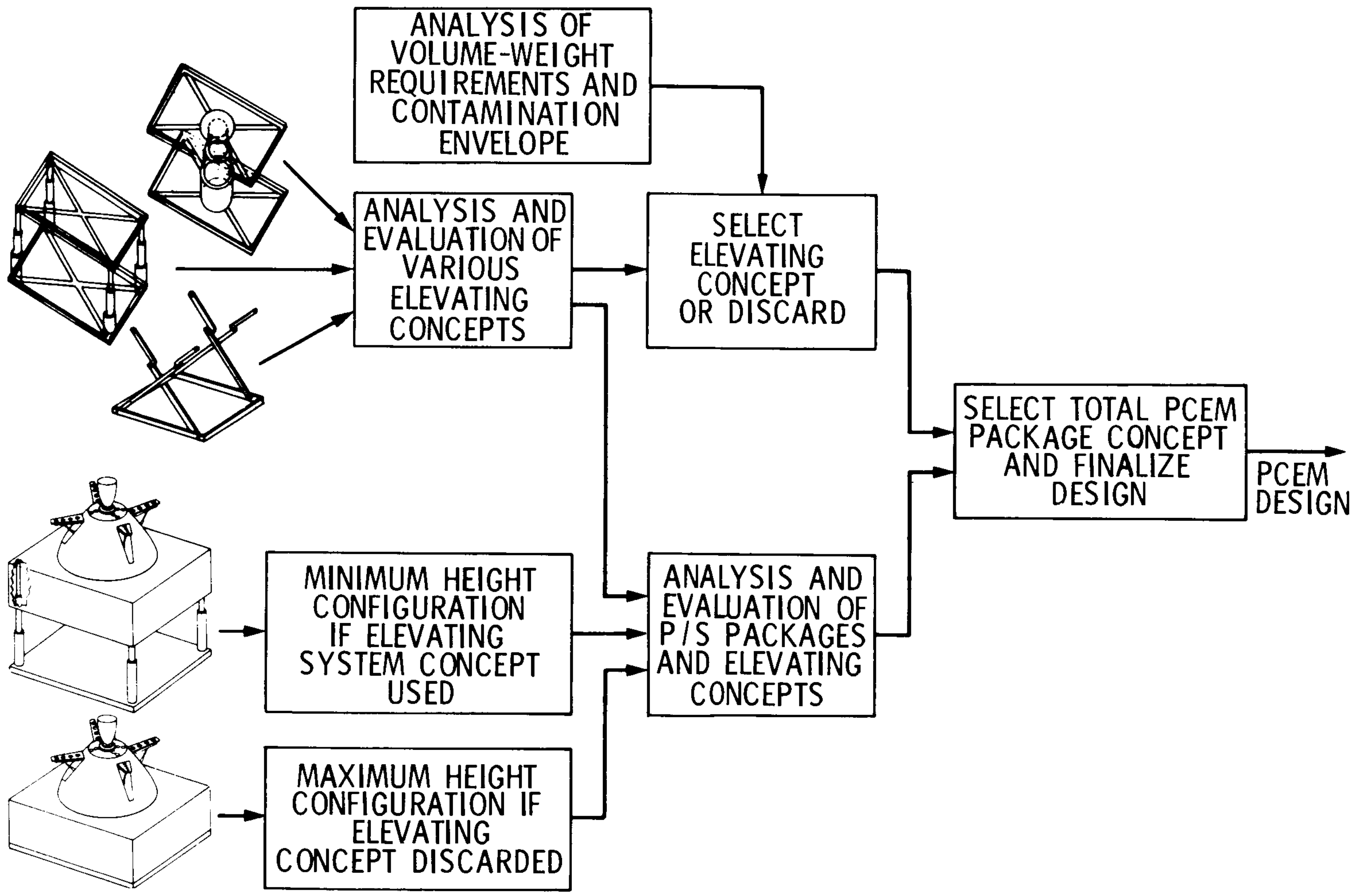


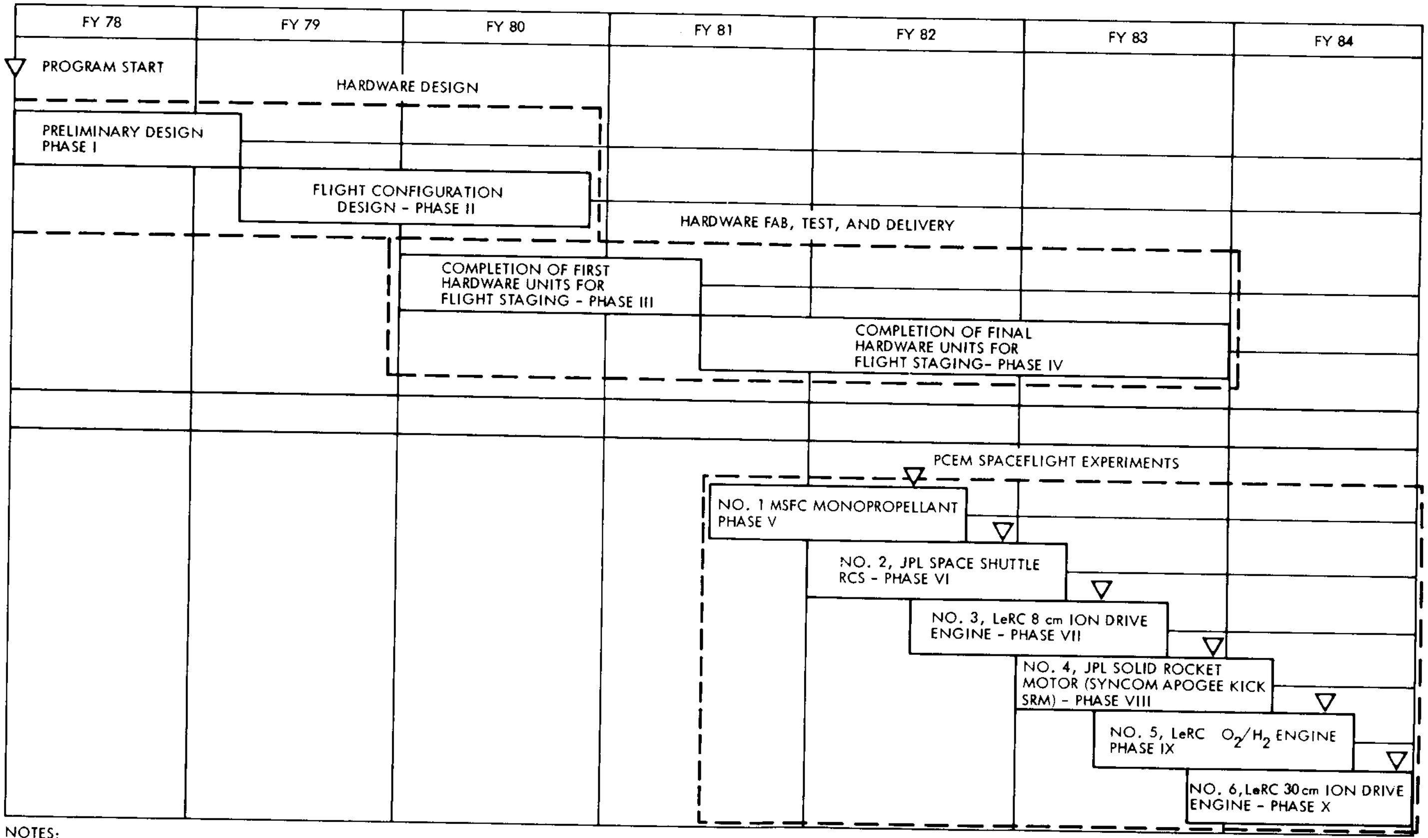
Figure 5. PCEM Concept Selection (Fixed or Elevating Configuration)

2.3.2 Basic Science Instruments Requirements. A basic complement of science instruments for plume measurements will be part of the PCEM facility. The quartz crystal microbalances (QCMs) with a refrigeration unit for temperature control requires some design, modification, and verification testing of currently or soon to be available off-the-shelf hardware. MSFC will use temperature controlled QCMs in the Induced Environment Contamination Monitor (IECM) for the initial Space Shuttle flights. These instruments are available from commercial instrument manufacturers. Options for refrigeration units include Stirling, Split Stirling, Vuilleumier, and Joule-Thompson refrigeration systems which have been used on various aircraft and spacecraft, and some are available from commercial manufacturers. The mass spectrometer also will require some design, modification, and verification testing of currently available hardware. Options for the mass spectrometer include the adaptation of the instrument which is included in the MSFC-IECM package, an instrument which is currently in the development test phase by Langley Research Center (LaRC), or some commercially available units. The temperature and pressure probes and the surface collectors will utilize currently available hardware which is to be adapted to the PCEM facility. The actual design details will be dependent upon the requirements established by the Principal Investigators for the experiment science from each NASA Center and by the PCEM Design Team for structural and mechanical considerations. However, the design, fabrication, and installation of these basic PCEM instrument units present no anticipated problems.

2.3.3 Prepackaged Propulsion Systems Requirements. The propulsion systems, as previously stated, are currently in development or in use. They will be modified and repackaged for mounting and operation in the PCEM facility. The Propulsion Section of each NASA Center will be responsible for providing the rocket engine systems. This responsibility also entails establishing the definition and requirements necessary for designing the propulsion system packages and establishing the interfaces for the installation and operation in the PCEM facility. The hardware is currently available, and no impacts on schedule or delivery are contemplated.

2.4 Flight Phase

The flight phase of the PCEM project will include a minimum of five flights. This minimum would be achieved with the successful installation and sequenced operation of the two ion drive engines [4.5×10^{-3} N (1×10^{-3} lb_f) and 1.3×10^{-1} N (3×10^{-2} lb_f)] into one package installed in the PCEM facility. Should this prove unfeasible, the systems would be designed for separate installations and flights. A preliminary schedule for the facility and the flights is shown in Fig. 6. Flights in excess of those required for the assigned propulsion systems would be reflights for a



NOTES:
▽ INDICATES "READY FOR FLIGHT"
FLIGHT EXPERIMENTS ARE ON "SPACE AVAILABLE" BASIS, SCHEDULE SHOWN IS MINIMUM WHICH CAN BE ACCOMMODATED

Figure 6. Summary PCEM and Flight Schedules

propulsion system which was returned for repair or modification following a flight malfunction, or flights for different types of propulsion systems. The PCEM-Shuttle/Spacelab flight operations include the flight staging operations, the Shuttle/Spacelab Level IV integration operation, the Shuttle/Spacelab Level III through Level I preflight operations, the flight and experiment, and the post flight operations.

The flight staging operations commence with the delivery of the flight hardware (i.e., PCEM Facility, Propulsion System, Ground Support Equipment, and Modification-Refurbishment Kits as required) to the flight staging area of JPL. This operation includes the integrating of the flight PCEM facility and Propulsion system, the checks and verification tests, the safety review, and flight acceptance. Subsequently, the integrated PCEM system would be delivered to the Shuttle flight integration site for Level IV integration operations. The Level III through Level I Shuttle/Spacelab operations will then be performed, culminating in the Shuttle/Spacelab flight to earth orbit. The spaceflight experiment tests in the Shuttle/Spacelab will be under the cognizance of the PI for the specific propulsion system assigned to the flight (i.e., each NASA Center with thruster experiment responsibility will have its own PI). The PCEM facility design will be such that the operation of the propulsion system and data acquisition will be essentially automatic with very little operational activity required on the part of the Payload Specialist at the PCEM control panel. The Specialist aboard the Shuttle will be in contact with the Payload Operations Control Center (POCC) for any special operating instructions from the PI. Upon return to earth and subsequent deintegration, the PCEM hardware will be depositioned after disassembly and it will then be returned to the responsible NASA Center. The data package will be forwarded to the PI for data reduction, analysis, and report.

3.0 CONCLUSIONS

The impingement of rocket exhaust gases on spacecraft surfaces may be the cause for many problems encountered on spacecraft and satellites. Among these are contamination of critical optical and mechanical components, disturbance forces and torques, high heat fluxes, and surface charging. Analytical or numerical models are utilized for the prediction of these effects, and the accuracy of these models must be ascertained by comparison with test data. The requirement for much of this data is for portions of the exhaust plume where the pressure level may be below the simulation capabilities of most ground test facilities. The PCEM facility will allow an investigator to test a propulsion system in the space environment, obtain the data needed for correlation with existing models, and update or revise these models as required. This facility is thus visualized as a valuable extension of present experimental capabilities into the real environment of space.

4.0 REFERENCES

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